

Table C-4

**Downlink Interference Into a SPACEWAY Earth Station Receiver
From an IRIDIUM Satellite**

Parameter	Detailed Consideration	Contribution to C/I Ratio
Spaceway Sat. Power P_1 , dBW	12.5	+ 12.5
Max. Iridium Sat. Power P_D , dBW	-3.2	+ 3.2
Spaceway Sat. Antenna Gain, dBi	46.5	+ 46.5
Iridium Sat. Antenna Gain, dBi	26.9	- 26.9
Bandwidth of Spaceway Signal, MHz	120	
Channel Sep. of Iridium Signals, MHz	7.22	
Bandwidth Factor, dB	12.21	- 12.2
Free-Space Loss, SPACEWAY	210.2	- 210.2
Free-Space Loss, IRIDIUM	182.2	+ 182.2
Worst-Case C/I, dB		- 4.9
Margin below Req'd 3.9 dB, dB		8.8

Annex D

Separation Distances of Earth Stations To Obtain Adequate Isolation Between Networks Through Earth Station Diversity

D.1 Introduction

In this annex the necessary separation distances between Earth stations of the IRIDIUM feeder-link system are determined, such that use of the appropriate Earth station would provide enough isolation between the IRIDIUM and SPACEWAY systems that there would be no harmful interference between them. This is determined for the following two scenarios:

- i) when the IRIDIUM system implements its APC system to the full extent to counteract interference from the SPACEWAY system, and
- ii) when the IRIDIUM system holds its automatic power control (APC) system in reserve to be used only to counteract atmospheric and rain attenuation.

D.2 Analysis Approach

The starting point of the analysis in this annex is the carrier-to-interference (C/I) equations in Annex C. These equations are generalized to be valid for offset angles of all antennas involved in the process. The resulting equations can be used to determine the necessary angles off boresite of any of the antennas involved to achieve any specified C/I level of either the IRIDIUM or the SPACEWAY system. At that point concentration is placed on the necessary off-boresite angle of the IRIDIUM Earth station, because it is the most directive antenna of either network in the process. Using the known antenna-discrimination characteristics of the IRIDIUM Earth-station antennas, the necessary off-boresite angles θ are determined to protect the IRIDIUM system, and to protect the SPACEWAY system, for each of the three scenarios outlined in the introduction of this annex.

The orbital characteristics of the IRIDIUM and SPACEWAY systems are then used to translate these required angle separations into required distance separations on the ground between the two IRIDIUM Earth stations used in the mitigation process. These results are then generalized to suggest the necessary separation of Earth stations in an IRIDIUM Earth-station complex to allow the mitigation process to be used by IRIDIUM to avoid interference with a number of geostationary (GSO) fixed satellite networks.

D.3 Generalization of the Interference Equations of Annex C

D.3.1 Simplified Equations, Not Taking Into Account Antenna Discrimination

The interference equations of Annex C in an uplink-interference situation are:

$$C = P_D - A_{CA} - A_{FS} + G_{DES} + G_{SC} \dots\dots\dots (C.1),$$

$$I = P_I - A_{CA} - A_{FS} + G_{IES} + G_{SC} \dots\dots\dots (C.2),$$

and

$$C/I = (P_D - P_I) + (G_{DES} - G_{IES}) + F_{BW} \dots\dots\dots (C.3),$$

where C is the desired carrier level at the interfered-with satellite,
 P_D is the Xmtr power level of the desired carrier,
 A_{CA} is the clear-air attenuation level in the transmission path,
 A_{FS} is the free-space loss in the transmission path to the interfered-with satellite,
 G_{DES} is the earth-station gain of the desired signal,
 G_{SC} is the satellite-antenna gain of the interfered-with satellite,
 I is the interfering carrier level at the interfered-with satellite,
 P_I is the Xmtr power level of the interfering carrier,
 G_{IES} is the earth-station gain of the interfering signal, and
 F_{BW} is a factor to account for the different bandwidths of the desired and interfering carriers.

The interference equations in an downlink-interference situation are similar but slightly more complex. They are:

$$C = P_D - A_{CA} - A_{D,FS} + G_{DSC} + G_{DES} \dots\dots\dots (C.4),$$

$$I = P_I - A_{CA} - A_{I,FS} + G_{ISC} + G_{DES} \dots\dots\dots (C.5),$$

and

$$C/I = (P_D - P_I) + (G_{DSC} - G_{ISC}) + F_{BW} - (A_{D,FS} - A_{I,FS}) \dots\dots\dots (C.6),$$

where most of the terms represent the same quantities as in the uplink equations, except that

$A_{D,FS}$ is the free-space-loss of the desired downlink signal, and
 $A_{I,FS}$ is the free-space-loss of the interfering downlink signal.

These last two terms were identical in the uplink situation, but are very different in the downlink situation.

D.3.2 Generalized Equations, Taking Into Account Antenna Selectivity

These interference equations are generalized to take into account possible offset of any of the antennas involved. In the uplink direction the carrier and interference levels are:

$$C = P_D - A_{CA} - A_{FS} + G_{DES}(\theta_D) + G_{SC}(\phi_D) \dots\dots\dots (D.1),$$

$$I = P_I - A_{CA} - A_{FS} + G_{IES}(\theta_{I,U}) + G_{SC}(\phi_{I,U}) \dots\dots\dots (D.2),$$

and

$$C/I = (P_D - P_I) + \{G_{DES}(\theta_D) - G_{IES}(\theta_{I,U})\} + \{G_{SC}(\phi_D) - G_{SC}(\phi_{I,U})\} + F_{BW} \dots\dots\dots (D.3),$$

where most of the terms are as defined above, with the following additional definitions for the angles involved:

- θ_D is the angle of the desired satellite off boresite of the antenna of the desired Earth station,
- $\theta_{I,U}$ is the angle of the desired satellite off boresite of the antenna of the interfering Earth station,
- ϕ_D is the angle of the desired Earth station off boresite of the antenna of the desired - signal satellite, and
- $\phi_{I,U}$ is the angle of the interfering Earth station off boresite of the antenna of the desired - signal satellite.

As in Annex C, it is noted that in Eq'n (D.3) the terms A_{CA} and A_{FS} are not present, since they are assumed to be similar if not common to the paths of the desired and the interfering carrier. The desired and interfering earth stations are assumed to be at similar locations, relative to the distances of either of the two satellites.

Another point to note is that the interference is determined in clear-air propagation conditions; no account is taken of rain attenuation in these calculations. This is because a rain event and an interference event are each independently events with low probability; the joint probability of the two independent events, each with low probability, is extremely low and so is ignored. It can be introduced later if required; to do so it is necessary to know the rain-attenuation statistics at the IRIDIUM earth station sites, taking into account the multiple terminals of the IRIDIUM earth-station complex.

The generalized interference equations in the downlink direction are similar but slightly more complex. They are:

$$C = P_D - A_{CA} - A_{D,FS} + G_{DSC}(\phi_D) + G_{DES}(\theta_D) \dots\dots\dots (D.4),$$

$$I = P_I - A_{CA} - A_{I,FS} + G_{ISC}(\phi_{I,D}) + G_{DES}(\theta_{I,D}) \dots \dots \dots (D.5),$$

and

$$C/I = (P_D - P_I) + \{ G_{DSC}(\phi_D) - G_{ISC}(\phi_{I,D}) \} + F_{BW} - (A_{D,FS} - A_{I,FS}) \\ + \{ G_{DES}(\theta_D) - G_{DES}(\theta_{I,D}) \} \dots \dots \dots (D.6),$$

where $\theta_{I,D}$ is the angle of the interfering satellite off boresite of the antenna of the desired Earth station, and

$\phi_{I,D}$ is the angle of the interfered-with Earth station off boresite of the antenna of the interfering satellite.

D.4 Antenna Characteristics

Equations D.3 and D.6 are general enough to consider interference mitigation techniques using the selectivity of any one of the four antennas affecting the interference process. These are the Earth station and the space station antennas of both the IRIDIUM and the SPACEWAY systems. The beamwidths of these antennas, taken from Reference 1, are as indicated in the following table:

Table D . 1

**Selectivity (Beam Width) of the Various Antennas
Involved in the Potential Interference Process
Between the IRIDIUM and the SPACEWAY Systems**

Antenna	Beam Size In the Uplink	Beam Size in the Downlink
IRIDIUM Satellite	5.0 °	7.4°
IRIDIUM Earth Station	0.24°	0.36°
SPACEWAY Satellite	1.0 °	1.1°
SPACEWAY Earth Station	1.1°	1.6 °

Of the four antennas, the most selective one is obviously the IRIDIUM Earth station antenna. That is probably so because the IRIDIUM feeder-link system uses relatively few Earth stations. (Five IRIDIUM Gateway Earth stations are planned in CONUS, for example, compared to the thousands of user Earth stations in the SPACEWAY system.) In any case, the 0.24° beamwidth in the uplink and 0.36° beamwidth in the downlink of that antenna offers the greatest potential for isolation of the two networks through antenna discrimination. The remainder of this annex pursues that possibility to the extent possible, limited only by whether or not the selectivity of the IRIDIUM Earth station antenna contributes to the interference process.

The main beam of the IRIDIUM feeder-link antenna can be modelled by the relations

$$G(\phi) = G_{\max} - 2.5 * 10^{-3} (D/\lambda)^2 \phi^2$$

$$= G_{\max} - K \phi^2 \quad , \text{ for } 0 \leq \phi \leq \phi_m \dots\dots\dots (D.7a),$$

$$= G_1 \quad , \text{ for } \phi_m \leq \phi \leq \phi_r \dots\dots\dots (D.7b),$$

and

$$= 32 - 25 \text{ Log}(\phi) \quad , \text{ for } \phi_r \leq \phi \leq 48^\circ \dots\dots\dots (D.7c).$$

based on the antenna pattern in Annex II of Appendix 28 of the Radio regulations. The first sidelobe gain G_1 is determined by the relation

$$G_1 = 2 + 15 \text{ Log}(D/\lambda) \dots\dots\dots (D.7d).$$

The angles ϕ_m and ϕ_r are specified by the relations

$$\phi_m = 20 (D/\lambda)^{-1} \{ G_{\max} - G_1 \}^{0.5} \dots\dots\dots (D.7e),$$

$$\text{and } \phi_r = 15.85 (D/\lambda)^{-0.6} \dots\dots\dots (D.7f).$$

The antenna's equivalent (D/λ) in the above relations can be estimated from its maximum gain by the relation

$$20 \text{ Log}(D/\lambda) = G_{\max} - 7.7 \text{ dB} \dots\dots\dots (D.8).$$

The IRIDIUM Earth station antenna has a boresite gain of 56.3 dBi in the uplink and 53.2 dBi in the downlink. From Eq'n (D.8) those Earth stations have a (D/λ) of 270 in the uplink and 188 in the downlink. This and the other antenna pattern parameters are given in Table D.2 for both uplink and downlink.

Table D. 2
IRIDIUM Earth Station Antenna Characteristics

Parameter	Uplink Value	Downlink Value
G_{\max}	56.3 dBi	53.2 dBi
D / λ	270	188
G_1	38.5 dBi	36.1 dBi
ϕ_m	0.313°	0.440°
ϕ_s	0.55°	0.68°

These values are used in Equations (D.7*) above to determine the required value ϕ_s to achieve isolation of the two networks through IRIDIUM Earth station antenna diversity.

It is noted that FCC Regulation 25.209 indicates an off-boresite antenna-gain 3 dB below that of Equation (D.7c) for off-boresite angles between 1° and 9.2°. However, the tighter constraints apply only to angles in the direction of the GSO. Since the IRIDIUM Earth-station antenna would have to operate in any combination of azimuth and elevation angle, it is concluded that the tighter constraints in the FCC's 25.209 do not apply, and so Equation (D.7c) is used for all angles ϕ in the range $\phi_r \leq \phi \leq 48^\circ$.

D.5 Isolation of the Two networks Through IRIDIUM Earth Station Diversity

D.5.1 Isolation When IRIDIUM Also Uses APC as an Interference-Mitigation Technique

Annex C discusses the possible use of transmitter power in reserve in both the Earth-station and space-station transmitters of the IRIDIUM system to overcome or at least to minimize to the extent possible the interference from SPACEWAY transmissions during an interference event. In doing so, the IRIDIUM system could overcome uplink harmful interference into its satellite receiver, and almost overcome the harmful downlink interference into its Earth station receivers. However, in the process it would cause significantly harmful interference into both space station and Earth station receivers of the SPACEWAY system. The question answered here is

In the event that the IRIDIUM system used its APC system to the extent possible to overcome harmful interference into its own network, what angle separation away from the SPACEWAY satellite being in its Earth-station antenna boresite would be necessary to avoid harmful interference in both networks ?

D.5.1.1 Uplink Interference

Interference events into the IRIDIUM satellite receiver will only occur when the SPACEWAY Earth stations, the IRIDIUM satellite, and the SPACEWAY satellite are in an approximately straight line. It is assumed here that the minimum operational elevation angle for the SPACEWAY system is 30° , so that elevation angle is included in estimating the IRIDIUM noise and interference budget.

As indicated in Table B-1, the IRIDIUM Earth-station power level to provide a C/N of 10.7 dB at 30° elevation angle is -18.7 dBW. The maximum power level is +12 dBW, so there is a 30.7 dB margin for interference mitigation at a 30° elevation angle under clear-sky conditions. Using the simpler Equation C.3 to determine the uplink C/I in the IRIDIUM system without antenna discrimination of any kind, the worst-case C/I is -14.3 dB. (See Table C-1 of Annex C.) If it is assumed that the operator of the IRIDIUM system would use the available APC to bring the uplink C/(N+I) back to +10.7 dB, the Earth station power would be increased by 25 dB.

An increase in IRIDIUM Earth-station output power by 25 dB would lower the C/I at the SPACEWAY satellite from +14.2 dB (before IRIDIUM APC was applied) to -10.8 dB after 25 dB of APC is applied. In this situation the above general question becomes

What is the necessary off-boresite angle of the IRIDIUM Earth-station to raise the C/I in the SPACEWAY satellite from -10.8 dB to +6.9 dB, the minimum level of C/(N+I) to continue operation during the short interference event?

That question can be answered by setting θ_D , $\theta_{I,U}$, and ϕ_D all equal to zero in Equation (D.3) and solving for the necessary $\phi_{I,U}$ to provide a 17.7 dB reduction in interference. Based on Table D.2 above, that is almost exactly the 17.8 dB ($G_{\max} - G_1$) difference of the IRIDIUM Earth-station antenna. In this case the necessary separation angle ϕ_S is equal to the Earth-station-antenna's angle ϕ_m , ie. 0.313° . It may be noted that an actual Earth-station antenna gain drops significantly below the G_1 level at angles slightly greater than ϕ_m , and then rises again to the G_1 level at the peak of the first sidelobe, so a separation angle of ϕ_m or perhaps slightly larger is considered adequate.

Thus a combination of the temporary use of 25 dB of a 30.7 dB APC budget in the IRIDIUM Earth station, and an IRIDIUM Earth-station-antenna separation angle of 0.313° from the direction of the SPACEWAY satellite, would eliminate uplink interference between the two networks.

D.5.1.2 Downlink Interference

In this section the necessary separation angle ϕ_S is determined to avoid harmful interference into both the IRIDIUM and SPACEWAY networks. As in the previous section, a 30° minimum elevation angle of both satellites during the interference events is assumed, based on the planned

location of SPACEWAY Earth terminals.

Without the use of APC to increase the the output power of the IRIDIUM spacecraft transmitter during an interference event, the worst-case C/I in the IRIDIUM system during that event would be -9.6 dB. (See Table C-3 of Annex C.) In such a scenario the worst-case C/I in a SPACEWAY Earth station would be + 10.2 dB, well above the minimum downlink C/(N+I) of 3.9 dB under worst-case conditions.

If IRIDIUM used their reserve APC satellite power to the maximum available, 15.1 dB at a worst-case 30° elevation angle, the IRIDIUM downlink C/(N+I) would be +5.5 dB, and as a result the SPACEWAY C/(N+I) would be reduced to - 4.9 dB, the value shown in Table C- 4.

If IRIDIUM Earth station antenna discrimination were used to raise the IRIDIUM C/(N+I) to the clear-air working level of 10.7 dB, 5.2 dB isolation would be required from the Earth-station antenna. Equation (D.7a) with (D/λ) equal to 188 indicates the required ϕ_s in this case; it is 0.243°.

If IRIDIUM Earth station antenna discrimination were used to raise the SPACEWAY C/(N+I) from its - 4.9 dB when full IRIDIUM satellite APC was applied to a minimum workable level of + 3.9 dB, an antenna isolation of at least 8.8 dB would be required. Again using Equation (D.7a) with (D/λ) equal to 188, the required angular separation ϕ_s would be 0.316°, slightly larger than that required to restore the performance of the IRIDIUM downlink to its clear-air operational level.

D.5.1.3 Summary of IRIDIUM Earth-Station Antenna Angular Separation Required When Full APC Is Used in the IRIDIUM System

Three antenna angular separations have been determined, each one to correct a specific short-term interference problem. These are:

- * 0.313° separation required to correct uplink interference in the SPACEWAY system;
- * 0.316° separation required to correct downlink interference in the SPACEWAY system; and
- * 0.243° separation required to correct downlink interference in the IRIDIUM system.

The necessary angular separation to correct all three problems would of course be the largest of the three, 0.316°.

D.5.2 Isolation When IRIDIUM Does Not Use APC as an Interference-Mitigation Technique

In the scenario examined here APC of the IRIDIUM system is NOT used as an interference-mitigation technique. It may be noted from Annex C that without the use of APC as an interference-

mitigation technique, interference does not reach harmful levels in the SPACEWAY system; it only reaches such levels in the IRIDIUM system. If this interference is to be avoided, it has to be done so through the use of antennas in the IRIDIUM system that do not point towards the interference. Specifically, harmful interference in the IRIDIUM system can be reduced to acceptable levels in the following two ways:

- * in the uplink, through use of spacecraft antenna isolation, and complementary use of an alternate Earth station antenna at the boresite of the space station antenna after it has been re-pointed to avoid the interference from SPACEWAY Earth stations; and
- * in the downlink, through the use of alternate IRIDIUM Earth station antennas at nearby locations to avoid an interference from the SPACEWAY space station, in the same way that interference is avoided in conjunction with use of APC in the IRIDIUM system.

D.5.2.1 Uplink Interference

As indicated in Table C-1 of Annex C, the uplink C/I ratio may be as low as - 14.3 dB in the IRIDIUM system when APC is not used in that system. To raise the C/(N+I) to the minimum +7.7 dB during clear-air propagation conditions, when the clear-air C/N is 10.7 dB, the ratio C/I would also have to be increased from - 14.3 dB to +10.7 dB, an increase of 25 dB.

Without an increase in uplink power in the IRIDIUM system, the only isolation possible from the SPACEWAY system would be through antenna isolation in the IRIDIUM spacecraft, not in the IRIDIUM Earth station. It is noted that the IRIDIUM satellite antenna gain is only 30.1 dBi at boresite, so the angular separation from transmitting SPACEWAY Earth terminals at the edge of the service area of a SPACEWAY service area, perhaps fairly remote from the IRIDIUM Earth station itself, would have to be such that the gain of the IRIDIUM spacecraft antenna in the direction of those transmitting antennas would be only about 5 dBi.

The sidelobe characteristics of the IRIDIUM spacecraft antenna are as described by Annex III of Appendix 29 of the Radio Regulations, which are the same as described in Equations (D.7*) above, except that the sidelobe gain for antennas with (D/λ) less than 100 is

$$G(\phi) = 52 - 10 \log(D/\lambda) - 25 \log(\phi), \text{ for } \phi_r \leq \phi \leq 48^\circ \dots\dots\dots (D.9a).$$

The IRIDIUM satellite antenna's boresite gain is 30.1dBi, which according to Equation (D.8) indicates a (D/λ) of 13.2. Thus Equation (D.9a) becomes

$$G(\phi) = 40.8 - 25 \log(\phi), \text{ for } \phi_r \leq \phi \leq 48^\circ \dots\dots\dots (D.9b).$$

Based on this equation, the required separation angle to achieve an antenna gain of only 5 dBi would be 27°. Note that this is 27° from any concentration of SPACEWAY Earth stations, which may be

considerably further than 27° angular separation from the IRIDIUM Earth station itself. To specify the separation distance on the ground it would be necessary to take into account the location of the SPACEWAY spacecraft antenna beams with respect to the possible future locations of IRIDIUM Earth stations, a complex and error-prone process.

D.5.2.2 Downlink Interference

In the downlink as well, there is harmful interference in the IRIDIUM system but not the SPACEWAY system. This will occur if the IRIDIUM Earth-station antenna that is tracking the IRIDIUM satellite finds the SPACEWAY satellite in its boresite, and if APC in the IRIDIUM system is not used as an interference-mitigation measure. Specifically, the worst-case downlink interference in the IRIDIUM system would be -9.6 dB, and in the SPACEWAY system the interference would be +10.2 dB.

To raise the downlink C/I in the IRIDIUM system to +10.7 dB, for the same reason as that discussed in Section D.5.2.1 above, an Earth-station-antenna discrimination of 20.3 dB would be required. Based on the information in Table D.2 above, the Earth-station-antenna discrimination angle would have to be such that the antenna was operating in the sidelobe $32 - 25 \text{ Log}(\phi)$ portion of its performance. An antenna discrimination $D(\phi)$ specified by the equation

$$D(\phi) \equiv G_{\max} - G(\phi) = G_{\max} - 32 + 25 \text{ Log}(\phi) \dots\dots\dots (D.10)$$

would be required, with G_{\max} equal to 53.2 dBi. To achieve a discrimination $D(\phi)$ of 20.3 dB, the required angular separation would be 0.92°.

D.5.2.3 Summary of IRIDIUM Earth-Station Antenna Angular Separation Required When No Use Is Made of APC in the IRIDIUM System to Combat Interference

In the uplink, the prime mechanism has to be IRIDIUM space station antenna discrimination when IRIDIUM Earth station APC is not used. To achieve the required discrimination, co-channel SPACEWAY Earth stations have to be 27° from the boresite of the IRIDIUM satellite's antenna.

In the downlink, IRIDIUM Earth station antenna discrimination is again the fundamental process for achieving isolation between the two networks. In this case an antenna separation angle of 0.92° is sufficient to achieve the required isolation.

D.6 Distances of Alternate IRIDIUM Earth Stations To Achieve the Required Earth Station or Space Station Angular Separation

D.6.1 Distances Required When Earth Station Antenna Discrimination is the Interference-Mitigation Measure Applied

An important parameter in the determination of the necessary distance between prime and alternate Earth station to achieve the necessary isolation between the two networks is the altitude of the IRIDIUM system: 780 km. At the very small angles involved in four of the five cases considered, i.e. 0.243° , 0.313° , 0.316° , and 0.92° , the angles are small enough that one can make the approximation that the angle (in radians), its Sine, and its Tangent, are all approximately equal.

In the simplest case, in which the IRIDIUM satellite is directly above the two Earth stations, the necessary distance between them such that they view that satellite with angles differing by a small angle ϕ is (780ϕ) km, when ϕ is expressed in radians.. For the angles 0.243° , 0.313° , 0.316° , and 0.92° the required separations between the Earth stations are 3.3 km, 4.3 km, 4.3 km, and 12.5 km respectively.

In the more realistic case, when the satellites have an elevation angle θ , this distance (780ϕ) km increases for two reasons. The first reason is that the distance to the IRIDIUM satellite increases from the minimum 780 km to the distance $780 / \sin(\theta)$. For the 30° minimum angle considered here, because the stated minimum elevation angle of the GSO satellite in the SPACEWAY system is 30° , the distance to the IRIDIUM satellite increases to 1560 km. Thus the minimum distances between the two Earth stations that are providing Earth-station diversity for one another increases to 6.6 km, 8.5 km, 8.6 km, and 25.0 km respectively for the four required angle separations 0.243° , 0.313° , 0.316° , and 0.92° .

There is another increase in these required distance separations that may be necessary. Determination of the distances 6.6 km, 8.5 km, 8.6 km, and 25.0 km assumed implicitly that the line joining an Earth station and the IRIDIUM satellite was perpendicular to the line joining the two Earth stations. That is of course possible under ideal conditions, and would result in the required distances 6.6 km, 8.5 km, 8.6 km, and 25.0 km. However, if the relative angles between the two Earth stations and the IRIDIUM satellite were the worst possible rather than the best possible, the two Earth stations and the IRIDIUM satellite would be in a vertical plane. In that case, the required distances would increase by a further factor $\{1 / \sin(\theta)\}$ or 2 in the case where θ was 30° . The distances would then increase further to 13.2 km, 17.0 km, 17.2 km, and 50 km.

These last distances are overly pessimistic for situations in which the interference events occur when the satellites are at an elevation angle of 30° , because the interference events occur at known locations of the satellites, determined by the location of the Earth stations and the GSO location of the SPACEWAY satellite. If interference with SPACEWAY satellites at 99°W and at 101°W were the only GSO-LEO interference events of concern in the design of the IRIDIUM system, the Earth

stations could be situated ideally to combat that potential problem, and the distances 6.6 km, 8.5 km, 8.6 km, and 25.0 km would apply. However, if the IRIDIUM Earth stations had to be located in such a way that interference with an unspecified number of GSO satellites had to be avoided, then perhaps the two IRIDIUM Earth stations should be located along an east-west line, and distances less than the set { 13.2 km, 17.0 km, 17.2 km, and 50 km } but greater than the set { 6.6 km, 8.5 km, 8.6 km, and 25.0 km } would apply.

The actual current situation involving IRIDIUM Earth station complexes is that each complex will include three Earth stations, with one peripheral Earth station located 34 nautical miles or about 63 km in an "x" direction and 15 miles or about 28 km in a perpendicular "y" direction from the central Earth station, and a second peripheral Earth station located 63 km in the opposite "x" direction and 27 km in the same "y" direction. These distances are presumably chosen to combat rain attenuation when the IRIDIUM satellite is at low elevation angles. These distances between the Earth stations, 68 km between each of the peripheral stations and the central station, and 126 km between the two peripheral stations, are significantly greater than the required distances discussed above. Thus it can be concluded that this Earth-station diversity technique can be employed without any further increases in Earth station separation beyond that chosen for mitigation of rain attenuation.

D.6.2 Distances Required When Space Station Antenna Discrimination is the Interference-Mitigation Measure Applied

IRIDIUM satellite antenna discrimination is the mitigation technique available to combat uplink interference from SPACEWAY Earth stations into IRIDIUM satellite receivers when IRIDIUM uplink APC is not used. As indicated above in Section D.5.2.1, this technique requires that the boresite of the IRIDIUM satellite antenna be such that the interfering SPACEWAY Earth stations be 27° off the boresite of the IRIDIUM satellite antenna. When the elevation angle between the prime IRIDIUM Earth station and the two satellites is 30°, this 27° angle off boresite rules out any possible IRIDIUM Earth station location in one direction. In the opposite direction a separation between Earth stations would have to be at least 844 km, and probably more to take into account the spread of SPACEWAY Earth stations over the SPACEWAY service area. These distances are not realistic, and so mitigation of uplink interference into the IRIDIUM satellite receiver through the use of IRIDIUM satellite antenna discrimination without the complementary use of IRIDIUM Earth station APC is not a viable technique.

D.6.3 Distances Required When the Satellites and the Primary IRIDIUM Earth Station are not Exactly in a Straight Line

The analysis in the above sections assumed implicitly that the path of the LEO satellite was the worst possible in terms of the LEO IRIDIUM Earth station causing or being subject to interference from the GSO SPACEWAY satellite. That worst-case arrangement is when the LEO satellite

temporarily intersects the line between the LEO Earth station and the GSO satellite. If there are only two LEO Earth stations involved in the Earth-station-diversity activity to mitigate potentially harmful interference, there is a possible alignment of the primary Earth station and the two satellites that requires an even larger separation between the two Earth stations to avoid harmful interference: that is an alignment in which the LEO satellite travels a path slightly different from that "in-line" path, such that when the LEO Earth station tracks the LEO satellite the GSO satellite is in the edges of the main beam of the Earth-station's antenna, and some isolation is provided by the antenna of the primary Earth-station's antenna, but not enough to avoid harmful interference to one or both networks. If that path is such that puts the GSO satellite closer to the boresite of the second satellite than the "in-line" path, a larger separation between the Earth stations on the ground would be necessary to avoid harmful interference entirely.

To summarize, if there were only two LEO Earth stations involved, and if they were to be placed at points far enough apart to be able to correct for harmful interference caused by any possible path of the LEO satellites, the distance would have to be twice that determined in Sections D.6.1 and D.6.2 above.

This concern applies, however, only to the situation in which there are only two LEO Earth stations in the LEO Earth-station complex. If there are three such Earth stations, as there are in an IRIDIUM Earth-station complex, the situation is improved to the extent that the above doubling of Earth station distances is not necessary. The reasoning on which this conclusion is drawn is as follows:

If the path of the LEO satellite is "between" the central IRIDIUM Earth station and one of the two peripheral Earth stations, and those two Earth stations are placed with separations described in Sections D.6.1 and D.6.2 above, neither of those two Earth stations may be able to become the active LEO Earth station without harmful interference occurring to one or both of the two networks. However, in such a situation the third Earth station is even further away from the GSO satellite, measured in terms of the angle between the boresite of that Earth station's antenna and the direction of the GSO satellite, if it is tracking the LEO satellite. Thus its ability to avoid a harmful interference situation is even better than if the LEO satellite's path was "in line" with the central Earth station.

The conclusion drawn from this consideration of different flight paths of the IRIDIUM satellite in a possible interference-causing situation is that when there are three LEO Earth stations involved in roughly a straight line, as there are in the design of an IRIDIUM Earth-station complex, the worst possible flight-path of the LEO satellite from the perspective of having to place the LEO Earth-station antennas far enough apart to avoid harmful interference into one or the other network is the flight path in which the satellite is temporarily "in line" between the central Earth station and the GSO satellite. That is the situation analyzed in Sections D.6.1 and D.6.2 above, and so the conclusions reached in these sections in terms of the necessary spacing between Earth stations apply to all LEO satellite flight paths, not just the "in line" one.

1

2

Sharing Study of IRIDIUM and SPACEWAY

Introduction

This paper describes a study of the interference condition between the IRIDIUM and SPACEWAY systems. Further, the study provides a quantitative assessment of various interference mitigation techniques.

Analysis Description

A computer simulation was developed to determine the interference levels into antennas of both systems as a function of time. The model is purely geometric in that all orbits and the earth are assumed to be spherical. At each moment in time, the relative positions of earth stations and satellites are calculated and the resulting interference level is determined. The full IRIDIUM constellation of 66 satellites is modeled along with a single SPACEWAY satellite. Earth terminals are assumed to be co-located. When the interfering signal bandwidth is less than the bandwidth of the victim receiver, enough interfering earth terminals are assumed to be present to match the victim signal bandwidth. The interference level is compared to the victim receiver noise temperature on a per Hz basis. Statistics are generated to show the percentage of time that a particular Io/No level is exceeded. System characteristics are shown in Table 1.

Figure 1 shows the result of the simulation for the SPACEWAY uplink interfering into the IRIDIUM spacecraft receiver with co-located earth terminals at 34 degrees north latitude. Overlaid on this figure is the result of a similar analysis performed by CSC. The two independent results show excellent agreement. Throughout this paper, only this link is considered. Results from the other links (IRIDIUM uplink into SPACEWAY and both downlink directions) are available and the conclusions drawn here are applicable to these other links as well.

Mitigation Techniques

As can be seen from Figure 1, the Io/No levels exceed the TG 4/5 recommended values. A number of mitigation techniques have been suggested to alleviate the interference between these types of systems. Path diversity, where alternate links are used (when available) to avoid the high level interference conditions is investigated here. Some definitions are in order. Referring to Figure 2, "satellite diversity" means that the IRIDIUM earth terminal could uplink to another satellite during the high interference events if another satellite is visible. "Site diversity" means that a second IRIDIUM earth terminal located some distance away from the primary site could be used for the uplink to avoid the in-line interference events. It should be reiterated that interfering earth terminals are assumed to be co-located at each site. Finally "path diversity" means that the best link among all earth sites and visible satellites is chosen. Each of these mitigation techniques is discussed below.

A. Satellite Diversity

Figures 3a through 3f show the improvement in Io/No due to satellite diversity as a function of earth station latitude. For instance, the bottom curve of figure 3a shows the improvement due to satellite

diversity at the equator. Not much improvement is seen because, at the equator, additional IRIDIUM satellites are visible only a small percentage of the time. As the earth terminal location is moved north, the same general trend is seen (figures 3b & 3c) until 45 degrees north is reached (figure 3d). Near this point, at least two satellites become visible at all times and this diversity technique shows substantial improvement in interference levels. At 60 degrees north, (figure 3e), satellite diversity essentially eliminates the interference condition. Figure 3f gives results between 35 and 45 degrees north at 2 degree increments and shows the "cliff-like" behavior of this technique near 45 degrees north. So this technique becomes very powerful for earth terminals located above about 45 degrees north (or below 45 degrees south).

B. Site Diversity

Figures 4a through 4e show the impact of site diversity, also as a function of earth station latitude. Referring to figure 4a, the top curve shows the interference condition at the equator with no diversity. The lower curves show the improvement when a second earth terminal added at 1 degree increments away from the primary site (1 degree is approximately 70 miles). The remainder of the curves in this set show the effects at higher latitudes. The results indicate that this technique provides substantial improvements in Io/No at all latitudes.

C. Path Diversity

Figures 5a through 5e show the improvements that can be expected using the path diversity scheme. At lower latitudes (figure 5a for instance) site diversity dominates since, as was shown earlier, satellite diversity does not provide much improvement at lower latitudes due to limited occurrences of multiple visible satellites. At higher latitudes (figures 5d & 5e) the combination of site and satellite diversity eliminates the interference condition even with small separations between diversity earth sites.

Conclusions

Although this analysis is preliminary and continuing, the results indicate that satellite and site diversity are powerful interference mitigation techniques. This analysis considers only the IRIDIUM and SPACEWAY systems, however the trends shown are applicable to other systems of these types.

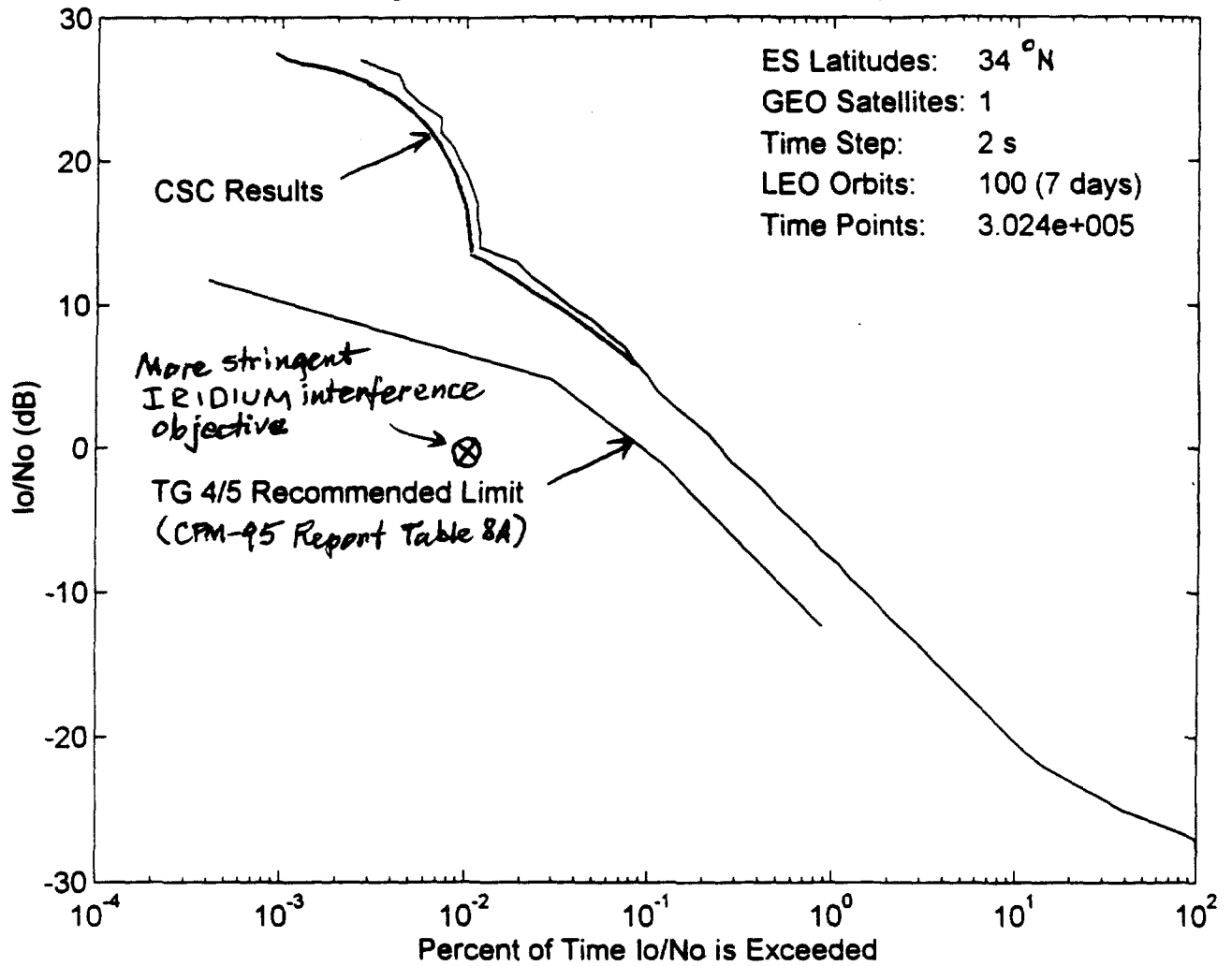
It should be noted that the sophisticated IRIDIUM system already has the capability to implement these mitigation techniques. Feeder link earth sites have multiple antennas to allow for normal hand-off, so the satellite diversity scheme requires no hardware changes to the earth site design. Similarly, the spacecraft carries multiple feeder link antennas also to allow normal hand-offs. Thus no hardware changes are needed on the spacecraft to implement the site diversity technique. Note also that site diversity is already planned for IRIDIUM to combat rain fades. Since path diversity is just a combination of the other two schemes, no hardware changes are necessary for this technique as well. Only very minor impacts to the IRIDIUM system (i.e., configure operational software to implement diversity) would be required to operate the system using these mitigation techniques.

Thus, without requiring hardware changes to either system, these techniques would allow co-frequency sharing between IRIDIUM feeder links and SPACEWAY.

Table 1 - System Characteristics

Parameter	IRIDIUM	SPACEWAY
Constellation		
Radius	780 km + earth radius	GSO radius
Period	100.8 minutes	24 hours
Planes	6	1
Satellites per plane	11	1
Plane spacing	31.6 degrees	n/a
Satellite spacing	360/11 degrees	n/a
Minimum elevation angle	5 degrees	10 degrees
Space Station		
Power into transmit antenna	-12.9 dBW	13 dBW
Bandwidth	4.375 MHz	120 MHz
Transmit antenna gain	26.9 dB	46.5 dB
Receive antenna gain	30.1 dB	46.5 dB
Receive noise temperature	1295 K	575 K
Earth Station		
Power into transmit antenna	-11.8 dBW	-4.7 dBW
Bandwidth	4.375 MHz	500 kHz
Antenna aperture	2.8 m (efficiency = 60 %)	66 cm (efficiency = 60 %)
Sidelobe characteristics	RR Appendix 29 Annex 3	RR Appendix 29 Annex 3
Receive noise temperature	731 K	175 K

Figure 1 - SPACEWAY into IRIDIUM Uplink



Satellite Diversity

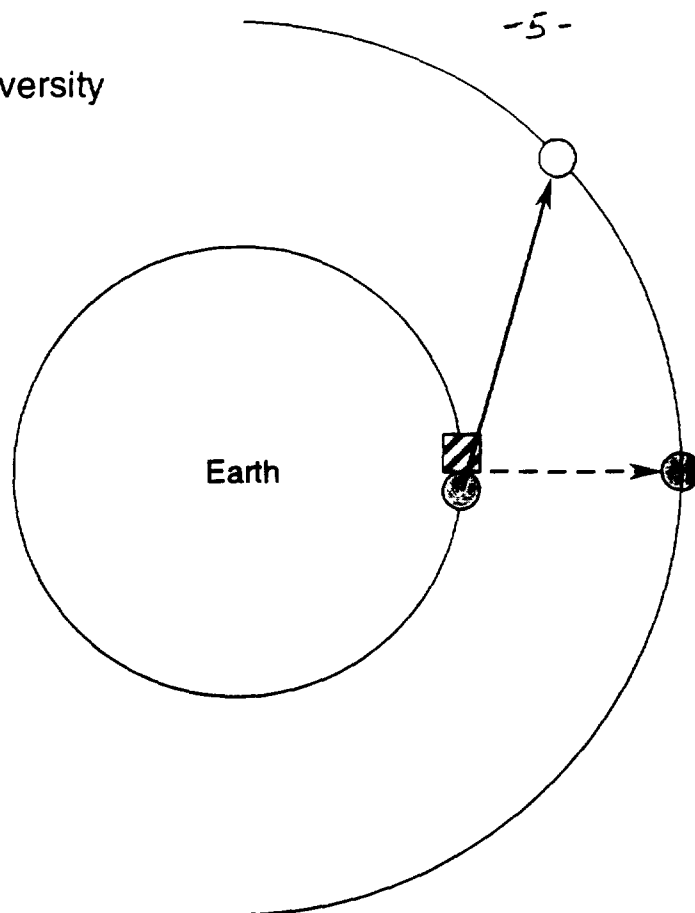




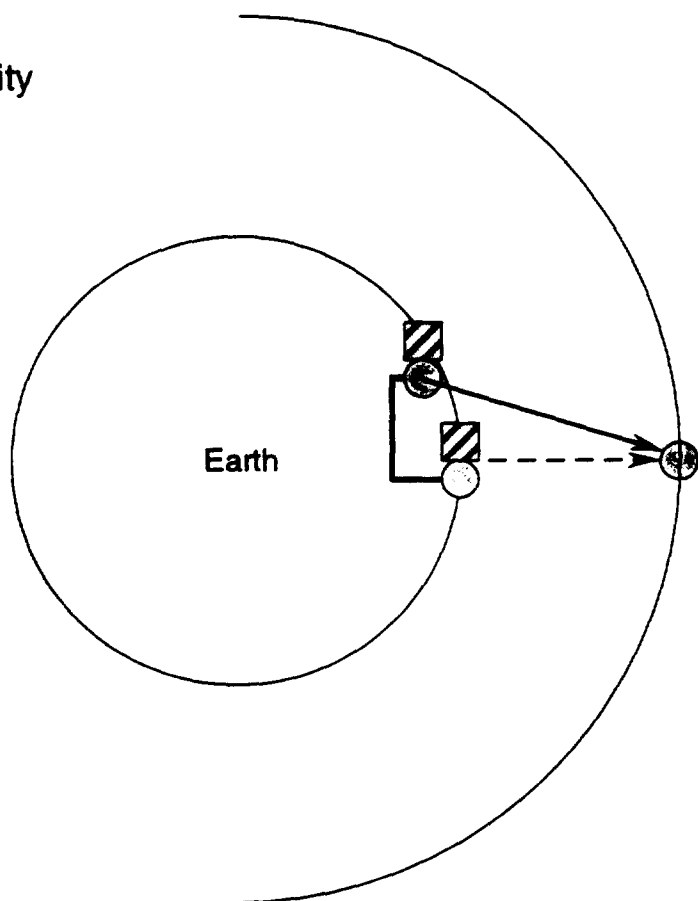






Figure 2
(Sheet 1 of 2)

-  Spaceway
-  Iridium
-  Interference path
-  Diversity path

Site Diversity



-  Spaceway
-  Iridium
-  Interference path
-  Diversity path

Path Diversity

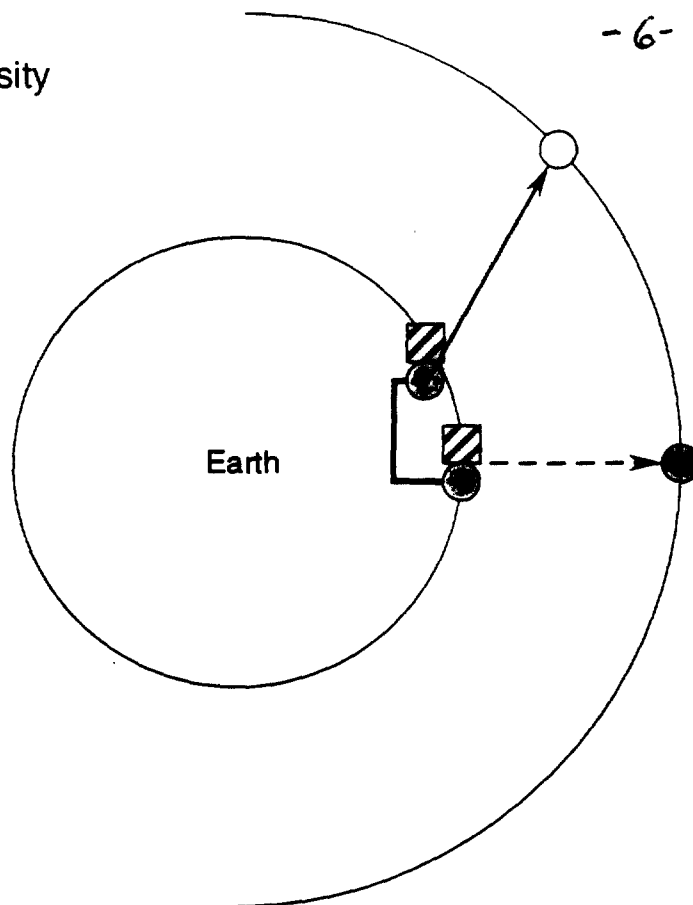


Figure 2
(Sheet 2 of 2)

 Spaceway

 Iridium

 Interference path

 Diversity path

Figure 3a - SPACEWAY into IRIDIUM Uplink Using Satellite Diversity

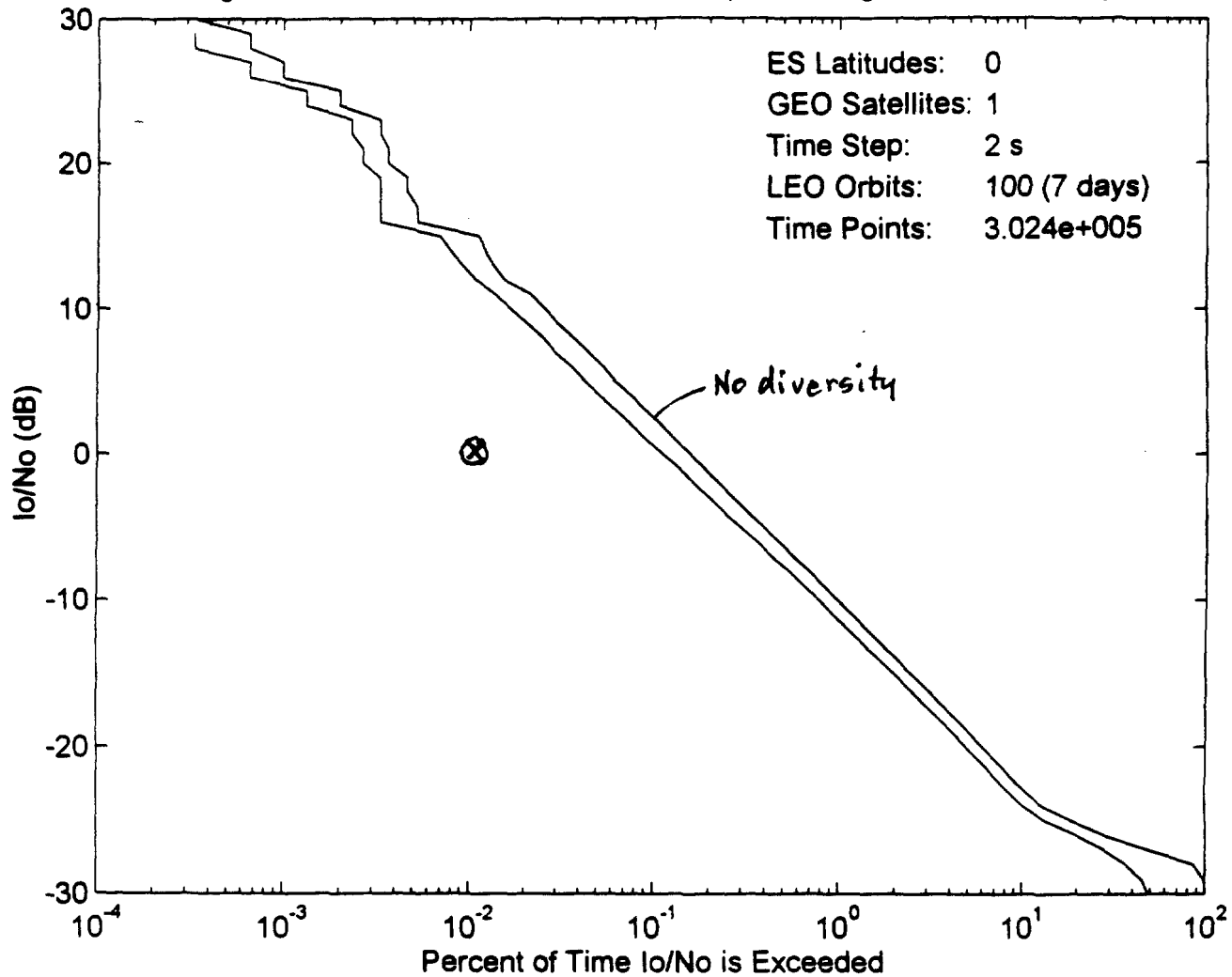


Figure 3b - SPACEWAY into IRIDIUM Uplink Using Satellite Diversity

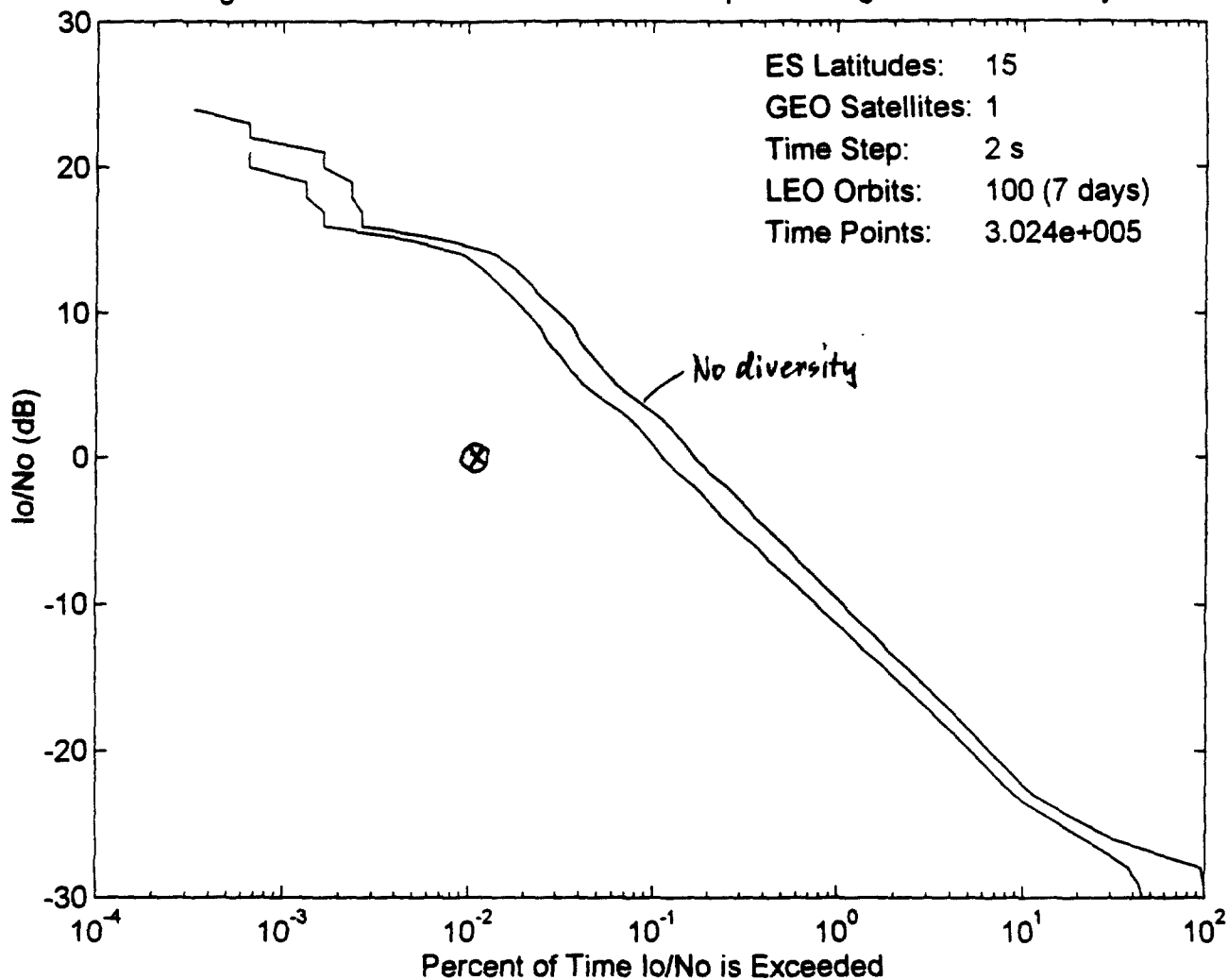


Figure 3c - SPACEWAY into IRIDIUM Uplink Using Satellite Diversity

